DEVELOPMENT OF A COMPREHENSIVE COVERAGE ASSESSMENT MODEL

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ABSTRACT

BBN has been tasked with developing a comprehensive coverage assessment tool for ocean acoustic monitoring. This tool will facilitate studies into the issues and sensitivities of using acoustic assets in the ocean to support a Comprehensive Test Ban Treaty. These issues include 1) understanding the sensitivity of signal structure to ocean environment variability as manifested through modal coupling, bottom and surface interaction losses and horizontal refraction and diffraction, 2) understanding the sensitivity of signal structure to source characteristics, and 3) designing detection and localization strategies which exploit to the fullest extent our understanding of the source and propagation characteristics.

In the first phase of this effort, the coverage assessment tool, which couples global and basin scale acoustic propagation models together with compatible source functions and an ocean database library, will be developed and benchmarked against available data. Once validated, the tool will be exercised to predict the signal and noise characteristics at existing and notional receiver locations, in order to identify regions where detection will yield particular challenges. Features of this tool will be software modularity and extensibility in order to facilitate the incorporation of new source functions, propagation models, databases and performance assessment modules as they become available.

1. OBJECTIVE

Comprehensive Test Ban Treaty verification requires the ability to monitor (detect, localize, and classify) nuclear testing worldwide. Covert nuclear tests, especially low yield explosions, performed at sea and detonated either in-air or underwater, are difficult to monitor using only land-based seismic sensors since energy from at-sea blasts is poorly coupled to seismic propagation paths. However, such energy often propagates well via waterborne paths, and can be detected at very long ranges using existing underwater surveillance assets such as SOSUS. Thus, a monitoring network comprising both seismic and underwater acoustic receivers can provide an effective and robust monitoring capability. Two key issues for such a system are identification of ocean regions in which propagation conditions prevent existing acoustic sensors from observing covert events, and the design of alternative acoustic sensor systems to provide coverage in such regions.

In August 1995, Bolt Beranek and Newman (BBN) was tasked to begin a twelve month effort to

- develop the initial version of a comprehensive model for evaluation of the ability of underwater sensors to detect and localize the detonation of nuclear devices in or above the ocean;
- validate this initial model by comparing its predictions with measured data; and,
- apply this model to two demonstration problems of operational interest, coverage assessment of selected existing assets, and gap analysis for a selected basin region.

This effort is viewed as the first phase of a multi-year program which will produce a full-capability, validated coverage assessment tool, and will involve more extensive analyses of operational monitoring issues. Deliverables from this initial effort will include both the findings and conclusions of the coverage analyses for the demonstration problems, and the first build of a fully operational and functionally complete software tool for coverage assessment with the following functions and features:

- Estimation of acoustic propagation characteristics (including travel time and attenuation) using state-of-the-art propagation models and high resolution environmental databases.
- Integration of GFI source functions
- Representation of the spatial and signal processing characteristics of acoustic receiver systems.
- Assessment of detection and localization coverage as a function of event yield and altitude/depth based on propagation predictions, receiver characteristics, and ambient noise properties.
- Simulation of received signal time series for examination and assessment of candidate discriminants for waveform-based classification and yield estimation.
- Determination of the confidence bounds for all estimates.

Our technical approach includes exploitation of the state of the art in propagation modeling at both long range (global scale) and medium range (basin scale, with poor coupling to the deep oceans) scenarios, representation of both waterborne propagation and teleseismic energy radiating back into the water column, and bottom and surface boundary interaction effects. We will capitalize on ongoing work in environmental database management software now underway at BBN to provide efficient architectures for incorporating a full spectrum of environmental acoustic databases in the coverage evaluation model, together with powerful visualization and manipulation tools. The model will also incorporate a flexible receiver specification algorithm to allow analyses of different receiver designs under variable noise conditions, and a means to assess the sensitivity of model predictions to environmental variability and model uncertainties.

This investigation will provide a tool for prediction of the signal to noise ratio of a waterborne nuclear event signature observed at the output of an acoustic sensor, and for simulation of the

received waveform itself. This tool will permit assessment of the coverage capability of existing underwater acoustic assets, which can be used both to identify gaps in coverage of particular areas, and to facilitate design of new assets to fill such gaps. This tool also supports operational monitoring, as it will allow the comparison of observed signals with simulated event waveforms (for potential discrimination) and estimation of yield. The user community for this product is expected to include AFPL/Geophysics Directorate, DOE, and AFTAC, as well as researchers at national laboratories and research universities.

2. FUTURE PLANS

Since this contract started in mid-August, the remainder of this paper describes our planned effort.

2.1 Overview of Approach — The development of the computational coverage evaluation tool requires both the resolution of various modeling and technical issues and the implementation of a flexible, extendible, and reusable software system. The approach is summarized below:

- Build a prototype version of the model, taking maximum advantage of existing software modules to achieve an early end-to-end capability. Identify and deal with baseline issues during this initial development process.
- Employ a considered software implementation approach based on a modular architecture and incremental development, test, and integration to ensure a reusable product.
- Validate the initial version by comparing results with measured data. Apply this validated model to two limited-scope test problems of operational interest (coverage assessment of existing assets, and gap analyses of selected basins), iteratively enhance and modify the system.

The result will be a deliverable coverage model, together with the results of the focused coverage evaluation test studies. The details of this approach are described in the following sections.

2.2 Coverage Model Description

The core evaluation metric of the area coverage assessment tool is signal-to-noise ratio (SNR) at the output of a single receiver; this quantity can be represented using the sonar equation for impulsive signals:

$$SNR = ESL - TL - (NL - AG) + PG, \qquad (1)$$

where ESL is energy source level, TL is transmission loss (attenuation), NL is noise level, AG is array gain (receiver spatial processing gain), and PG is receiver (temporal) processing gain (all quantities are in dB). SNR is interpreted as the peak value of the receiver output, relative to background, and may be defined for a complete event, or for a single component phase.

A variety of potential metrics might be used to characterize receiver or coverage performance; SNR was selected because it is intuitive, relatively unequivocal, and can be related to a number of other performance metrics, such as detection probability and arrival time accuracy. Calculation of SNR requires computation and combination of the terms on the right-hand side of (1); this process is reflected in the architecture of the computational model, as illustrated in Figure 1. Each of the component blocks of the model is discussed in a subsequent section, as noted in the Figure.

In operation, the area coverage evaluation tool functions as follows. The source function, a "starter field" for linear propagation to long range, defines the ESL over a cylindrical surface in the water column as a function of range, depth, and frequency. This source function is the input to a range dependent propagation model which estimates the complex propagation transfer function, and hence transmission loss (TL) and signal travel time, at multiple frequencies along selected bearings from the event position. The result is the estimated propagation transfer function, for each frequency, to

any selected range and depth along these radials. By interpolating between radials, we can determine received signal level and travel time from any point in the ocean to the receiver location.

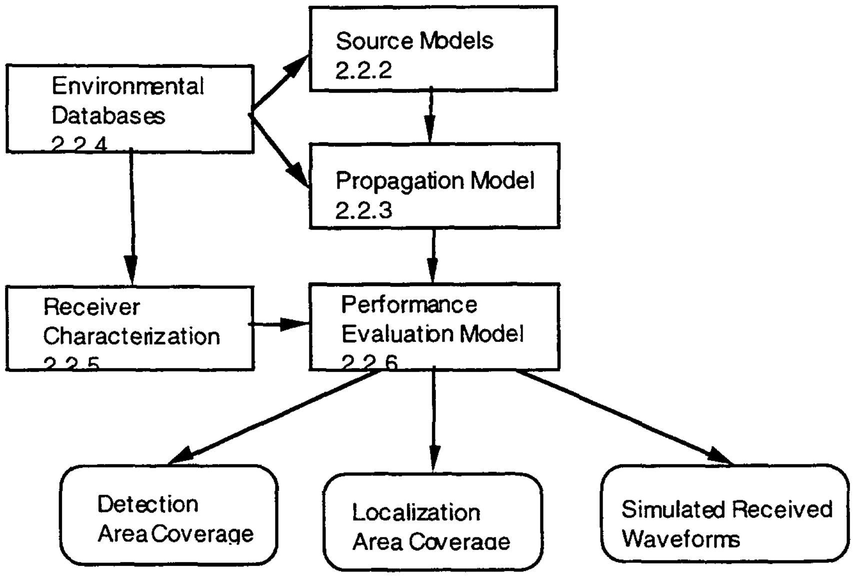

Figure 1. Simplified Block Diagram of Coverage Assessment Model

Receiver spatial and temporal processing characteristics define the array gain, AG, and processing gain, PG. Acoustic receivers typically employ linear arrays of hydrophones and phased-array processing for noise rejection and coarse bearing estimation. These results are combined with the characteristics of the local ambient noise field and the signal to compute SNR using (1). Hence, SNR is specific to both receiver configuration and location for a given event.

Calculation of SNR occurs in the Performance Evaluation module. Single-receiver SNR may be used directly to define detection and localization coverage, converted to another metric, or combined with SNR estimates for other receivers at other locations to compute the performance of an acoustic sensor network. Anticipated data products include geographic contour maps of detection and localization coverage regions, and estimates of the received waveform. Waveform simulation can be very useful for identification of discriminants and model fidelity assessments; the cover of this proposal illustrate the prediction fidelity which can be achieved under some circumstances.

Finally, observe that environmental databases play a central role at all stages of the calculation. Proper use of database information, e.g., selection of the appropriate bathymetry, and a robust interpolation scheme, is a critical development issue.

An advantage of this model implementation is that its modules can be transitioned directly into a nuclear blast detection/evaluation system. For example, given a signal arrival that is both detected and localized, the propagation model can be used to remove the impact of the propagation medium (TL) for each detected arrival, and the resulting ESL estimate can be converted to estimated yield.

2.2.1 Source Models — The principal development effort for the source portion of the model is to couple the GFI source functions to the acoustic propagation medium. The most significant issues are coupling to the bottom, and transmission through the air-sea interface for air blasts. Coupling to ocean bottom seismic waves will be dominated by interactions between the shock and bubble pulse waves and the bottom in the region directly below the detonation. Especially in shallow water, these incident waves will be moderate to strong shock waves. For detonations not too far from acoustically-fast bottom interfaces, up to a third of the radiated sound energy may be coupled into

the bottom and then radiated from it. Those paths which have high group speed due to propagation in the sediment, crustal layers 2 and 3, and the upper mantle result in precursor waves at the receiver. These precursors may provide important classification clues at shorter ranges where they can be detected despite their higher effective attenuation (due to crustal interface roughness and intrinsic attenuation coefficient). They will be particularly important for localization and discrimination at basin scales (ranges < 150 nm).

2.2.2 Propagation Models — Reliable coverage assessment requires an understanding of propagation at both basin and trans-oceanic scales. BBN will employ state of the art acoustic models at these two scales, identify requirements for further model refinement, and explore means of utilizing various ocean environmental databases with these models.

Basin Scale Propagation -- In basin propagation, the signals received from large explosions are typically the sum of seismic phases and dispersive acoustic normal modes. Propagation at low frequencies follows a single horizontal path between the source and receiver. At this scale it will be possible to model the acoustic propagation accurately enough to place precise bounds on the location of the source, and therefore the source strength, using a small number of sensor elements.

Acoustic propagation at basin scales is well understood, and there are a number of models for propagation in range dependent, azimuthally uncoupled environments, an approach termed "N by 2D". Methods for incorporating the elastic sub-bottom are also available for horizontally stratified media and for general range-varying layering under the parabolic approximation. Full three dimensional propagation modeling has recently become computationally feasible, and may be used to model diffraction of sound exiting enclosed basins through narrow outlets. Research issues for the basin scale center on understanding the excitation and subsequent waterborne detection of seismic phases, modeling diffraction of acoustic energy due to highly variable bathymetry, and modeling down slope propagation of acoustic energy out of a shallow region into the basin. In addition, current research addresses integration of database descriptions of the ocean into the various ocean acoustic models, with emphasis on empirical orthogonal functions (EOF) as an efficient basis for representing observed vertical and lateral inhomogeneity in ocean properties.

For predictions at these scales, existing N by 2-D models, such as KRAKEN (a normal mode model) or Finite Element Parabolic Equation (FEPE), and existing seismo-acoustic models, such as OASES, will be used. The importance of deep refracting seismic paths on location and yield estimation will be quantified. The seismo-acoustic models will to investigate the seismic propagation issues, and all propagation models will be used to evaluate horizontal and vertical diffraction effects as mentioned above.

Global Scale Propagation -- At global scales, the geometry of the earth cannot be neglected and the effects of horizontal refraction due to lateral sound speed and bathymetry variations become important. Significant shadow zones can exist between source and receiver, due to the intrusion of continents, islands and shoaling bathymetry into the propagation path. Hence, there will be regions where detonations cannot be observed by specific sensors. Although seismic phases may not be detected at global ranges, horizontal and vertical multi-path may be exploited to help determine the range to the source.

Recent interest in monitoring the temperature of the oceans has required substantial refinement of existing methods of modeling global scale propagation. The assumption that acoustic rays followed great circle paths proved inadequate to describe the signal structure for propagation between sources and receivers half a world apart. Subsequent work has shown that horizontal refraction around continental margins, as well as the non-sphericity of the earth, can account for most discrepancies between the observed signal structure and the previous model predictions. Models employing the parabolic approximation in polar and azimuthal coordinates include the full effects of horizontal

diffraction, provide direct estimates of transmission loss, and hence promise additional insight into the quality of the ray-based horizontal refraction predictions, the present computational standard.

Trans-global acoustic propagation studies will employ state of the art horizontal ray/vertical mode and PE-based acoustic models available from NRL. We will address the sensitivity of travel times, modal content and horizontal multi-path predicted by these models to environmental variability and database interpolation. The adequacy of the adiabatic mode assumption used in ray/mode propagation models will be evaluated given the importance of mode coupling in regions of rapidly varying bathymetry.

The adequacy of a ray model to describe horizontal propagation paths is also a key issue, as is a means of interpreting the absolute shadow zones predicted by ray theory. Also of concern is ray instability, or sensitivity to initial conditions: only if rays are stable can ray models provide good time of flight estimates for hypothetical source locations and available receiver assets. Ray stability will be addressed in concert with the evaluation of database interpolation techniques used to obtain environmental data on the computational grid. Ray sensitivity to interpolation schemes can be as damaging as sensitivity to initial conditions. The tool will enable such sensitivities to be identified by facilitating the comparison between ray and full wave solution techniques.

As with the basin scale problem, the details of the arrival structure at trans-oceanic scales will depend on the modal excitation spectrum of the source function. Basin-scale modeling efforts will aid in identifying the modal mix of the starting field for the trans-global problem. In addition, the local diffraction effects analyzed in the basin scale studies with N by 2-D or 3-D full wave solution techniques will be useful for estimating the global starting field when nuclear devices are detonated in the presence of highly variable bathymetry or in shallow water.

Principal research issues at both scales are summarized in Table 1. For both scales, the sensitivities of the propagation characteristics to the following variables will be addressed as part of the coverage evaluation and model validation efforts:

- Source function and location
- Modal phase velocity structure and variance in the oceans
- Sound speed, bathymetry and bottom properties between the source and receiver
- Bottom, surface, and volume loss mechanisms.

Issue	Basin	Global PE	Global Ray
Transmission loss modeling along horizontal rays			•
Interpretation of absolute shadowing and caustics			•
Adequacy of adiabatic mode assumption for vertical field component		•	•
Sensitivity to database interpolation methods	•	•	•
Travel time and path sensitivity to small perturbations in environmental characteristics			•
Computational efficiency	•	•	•
Seismic phase excitation	•		
Diffraction in variable bathymetry	•	•	•
Down-slope propagation from shallow regions into a basin	•		

Table 1 - Propagation modeling research issues in support of coverage assessment.

2.2.3 Environmental Databases — A critical element for performance prediction is the ability to rapidly visualize, analyze and incorporate large quantities of historical environmental data into numerical propagation, and detection coverage models. BBN has already developed such a database manipulation capability under the ONR Long Term Acoustic Study (LTAS) and ARPA Shallow Water Area Surveillance (SWAS) programs. This geographic information system, called DBTool, comprises a collection of environmental databases, a baseline set of propagation models, and an extensive set of tools for data analysis and visualization. The global databases in DBTool are listed in Table 2; these comprise the baseline for the coverage assessment tool. These databases include information on environmental factors affecting low frequency ambient noise (shipping densities), high frequency ambient noise (wind speed and rainfall), and acoustic propagation (sound speed profiles, bathymetry and sediment characteristics).

Database	Description	Resolution (min)
DBDB-C	Bathymetry	5.0
GDEM	Sound speed profiles	30
LFBL	Low Frequency Bottom Loss	5.0
HWS	Historical Wind Speed	60
HITS	Historical Temporal Shipping	60
ETOPO5	Bathymetry	5.0
NODC	Sound Speed profiles	Variable
GDS	Global Daily Summary (Temp/Precip)	Variable
MGG	Sediment	Variable

Table 2 - DBTool environmental databases to be incorporated in the coverage assessment model

DBTool also provides a means to couple such environmental data directly into various acoustic models using the N by 2D approach for determining geographic coverage, which will be enhanced to support true 3D models for this project. The models currently integrated with the databases include SUNRAY (a BBN-developed range-dependent ray trace model), FEPE, and KRAKEN. Using this system, it is possible to interactively extract, visualize and analyze data for a given region with a graphical user interface. Once the oceanographic data is extracted, N by 2D predictions of the acoustic propagation may be performed by specifying the location of the source and N radials from the source.

2.2.4 Receiver Characterization — This module specifies the acoustic receiver characteristics required for computation of SNR. The baseline receiver model described embodies the essential properties of typical receivers, and may be extended as circumstances indicate. Potential extensions include those required to support fine bearing (arrival azimuth) estimation, or integration windows matched to the anticipated signal envelope (phase structure).

Spatial processing — Typical acoustic receivers employ arrays of hydrophone elements in various configurations, with linear arrays being most common. Such sensors are processed as phased arrays to improve SNR against ambient noise; the spatial processing advantage provided by such a beamformed array is characterized by its array gain, which is the noise level of a beam output relative to an omniphone. Ocean ambient noise over most of the frequency range of concern, 1-200 Hz, is principally due to distant shipping, resulting in a noise field concentrated near the horizontal which varies in both azimuth and frequency. Hence, achievable array gain depends on the spatial distribution of the noise field, the spatial response of the phased array (the beampattern), and the arrival direction of energy from the source (e.g., little spatial gain may be achieved if a dominant noise source lies between the source and the array).

The spatial processing characteristics of the receiver will be specified by the configuration of the array elements (relative position, and absolute location and orientation), and by the processing algorithm used in the beamformer, typically including spatial shading or weighting functions, number of beams formed and pointing directions. These may be summarized by the directional response pattern of the array/beamformer as a function of steering and incident directions, and frequency; this function may be provided or computed from the parameters of the receiver.

Temporal processing — Detection of a nuclear blast event can be characterized as detection of a transient whose bandwidth and duration may be (approximately) known beforehand. A reasonable baseline signal processing chain for such a detection problem is a filter-squarer-integrator: the bandwidth of the filter and the duration of the integrator are matched to expected bandwidth and extent of the transient. Hence, the signal processing portion of the receiver will be characterized by filter bandwidth (plus any frequency shaping, if that is used) and the duration of the integration.

2.2.5 Performance Evaluation Model — The two principal aspects of performance, detection and localization, are addressed in this module.

Detection — Detection performance is characterized by signal-to-noise ratio, SNR, as described in Section 2.2.1. SNR is the (peak) amount of event signal energy captured by the receiving system, relative to the background noise level. Peak signal energy is a function of both the signal properties and receiving system bandwidth and integration time, and also depends on the sensor's spatial response. Background noise level is determined by the spatial distribution of the ambient noise field, the spatial noise response of the receiver, plus the receiver bandwidth and integration time.

Calculation of SNR from (1) is relatively straightforward, but two terms in (1) deserve particular note. The term (NL - AG) represents ambient noise level in a beam, but is calculated by integrating the noise spatial density over the array beampattern. Computation of this value at band center usually suffices; for very broad bands more complex methods must be used. PG represents the gain of the temporal processing receiver, which is typically 10 log (TW), where TW is the time-bandwidth product of the receiver. PG may also include, however, the effects of mismatch to the received signal, e.g., bandwidth mismatch, which will reduce the effective ESL. Depending on the complexity of the received waveforms and the degree of mismatch expected, it may be necessary to determine PG by processing the simulated waveform through the receiver processing chain.

SNR may be transformed into detection probability, but this requires a model for the receiver output statistics. BBN has used a low degree-of-freedom Gaussian (chi-square) distribution to model receiver performance for explosive signals at moderate ranges, but different fluctuation statistics may be encountered at extended ranges. Transformation to probability also requires specification of a detection threshold, which is problematic: transient receiver threshold settings are dominated by false alarm considerations, and are usually determined empirically.

Each individual performance computation yields an SNR value for a fixed receiver configuration and location, and for a fixed event location, yield, and depth/height. Multiple computations provide a set of SNR values which may be presented in various ways. Two data products are envisioned:

- a geographic plot of SNR contours for a specific receiver location/configuration, corresponding to different locations of the event (for evaluation of existing assets); and
- a geographic plot of SNR contours for a specific event location, yield and depth/height for various receiver locations (for evaluation of alternative locations for new sensors).

This methodology may be extended to evaluation of multiple-sensor (field) coverage, by combining the SNR sets computed for different receivers. Potential field performance metrics include: contours of the minimum SNR seen over the field (very conservative); and, for M of N detection criteria, contours of the Mth largest SNR value over the field.

Localization — The most appropriate metric for localization coverage is area of uncertainty (AOU), which summarizes the effect of all the uncertainties in the localization calculation, including model uncertainties, e.g., uncertainties in the assumed propagation speeds. If localization estimates are provided by beam intersection, the AOU is defined by the overlap region of the beams from all arrays which detect the event (have a minimum specified SNR). Alternatively, localization may be based on time difference of arrival of one or more phases at multiple receivers, in which case signal-to-noise ratio, and signal bandwidth/wave shape as well as sensor-event geometries determine AOU. Similarly, range estimates may be obtained from the relative time of arrival of different phases at each array; the AOU is then determined by range intersection uncertainties. BBN has developed AOU computation procedures for similar mixed measurements which occur in multistatic active sonar systems, and will apply these results to the coverage evaluation problem.

2.3 Model Implementation — The model will consists of a shell, written in the C^{++} object-oriented programming language, and interfaced with existing propagation models written in C or FORTRAN. The shell will employ Matlab for display and analysis of results, and for database interfaces. Careful software design will provide a modular, transportable, flexible architecture which will allow easy inclusion of additional or modified model components or extension to existing models. The bulk of the software development effort will involve the performance modeling shell and integration and enhancement of existing propagation codes; only a modest amount of new code development is anticipated. Development will draw heavily on DBTool, BBN's existing software for management of acoustic performance prediction databases. The target processor for this project will be a dual-processor Sparc-20. If more extensive computational facilities are required, we intend to utilize an existing distributed network of Sun workstations during off-peak hours.

2.4 Coverage Investigations — Two investigations of coverage performance will be performed. These investigations will serve as a testbed for exercise and development of models and analysis capabilities while addressing, on an example basis, problems of practical interest. Incremental enhancements will be made to the model as indicated by the results of these studies.

- Coverage analysis of selected existing assets - For a selected set of existing acoustic surveillance assets (e.g., SOSUS arrays), evaluate detection and localization coverage which is attainable in selected ocean areas. This study employ reciprocity, in which the source event is placed at the sensor location and vice-versa, to achieve a computational efficiency.

- Gap analysis for selected basins - Identify candidate receiver locations and characteristics for the detection of events of specified yield and height/depth in selected basin areas.

These investigations will include the evaluation of confidence or error bounds on predicted performance, and on the intermediate predictions of transmission loss, arrival time, and waveform shape. Although acoustic detection performance in the ocean exhibits statistical fluctuations of practical concern, the effects of database inaccuracies and model imperfections may dominate predictions of performance. BBN will address this issue in two ways. First, performance prediction runs will be made multiple times with perturbed database values to establish an ensemble of "reasonable" predicted values. The objective here is to model the error due to uncertainties in the databases. Second, we will compare predicted values with actual observation of explosive event waveforms, amplitudes, and travel times; this will validate the models by identifying large errors, and establish empirical variability. Presumably, empirical variability will be larger than that due to perturbations, and the residual will comprise the sum of statistical variability and model inaccuracies.